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## Evolution of the Illawarra Escarpment terrain

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# EVOLUTION OF THE ILLAWARRA ESCARPMENT TERRAIN

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## ABSTRACT

Drawing on the disciplines of stratigraphy, plate tectonics and passive margin development, the evolution of Illawarra Escarpment terrain in the southeastern corner of the Sydney Basin is placed within known geological constraints. The development of the terrain begins with the initial deposition of the early Permian Sydney Basin sequences, into what was a developing (yet subsequently failed) rift fracture within the eastern side of the Gondwana supercontinent (the Sydney – Gunnedah – Bowen Basin trough), through to the eventual rifting of the existing continental margin and opening of the Tasman Sea around 70 million years ago in the vicinity of Sydney. The timing of this rifting and a regional cross-section across the coastline and out into the Tasman Basin allow the assessment of a long term rate of escarpment retreat of 0.6 m per 1000 years. Cenozoic, Quaternary and in particular Holocene climate variability and the attendant sea-level changes and the impact these have on the escarpment terrain is demonstrated. It is shown that the Illawarra Escarpment has evolved as a result of the natural processes of escarpment retreat and associated slope processes, coastal erosion and marine abrasion. The escarpment can be considered to be of Quaternary age albeit with its precursor slopes extending back into the Neogene period.

A landslide inventory managed by the University of Wollongong currently identifies 665 landslide locations and a total of 1050 landslide events in this region over the last 120 years. This inventory facilitates the assessment of contemporary escarpment retreat rates. These rates range from 0.1 m to 1.0 m per 1000 years. Whilst the process rates will vary by small amounts elsewhere along the coastline, the same logic and discussion applies for much of the south-east coast of Australia.

## 1 INTRODUCTION

The Illawarra Escarpment and its coastal plain support the city of Wollongong, 70 km south of Sydney, New South Wales (NSW), Australia. Over the last 150 years of settlement, the population of the Wollongong area has increased to about 200,000 people. The coastal plain is triangular in shape, is up to 17 km wide in the south and extends north to Thirroul, with a coastal length of 45 km. To the north of Thirroul, urban development exists on the mid to lower slopes of the escarpment. The coastal plain is bounded to the north, west and south by the erosional Illawarra escarpment ranging in height from 300 m up to 500 m as illustrated in Figure 1.

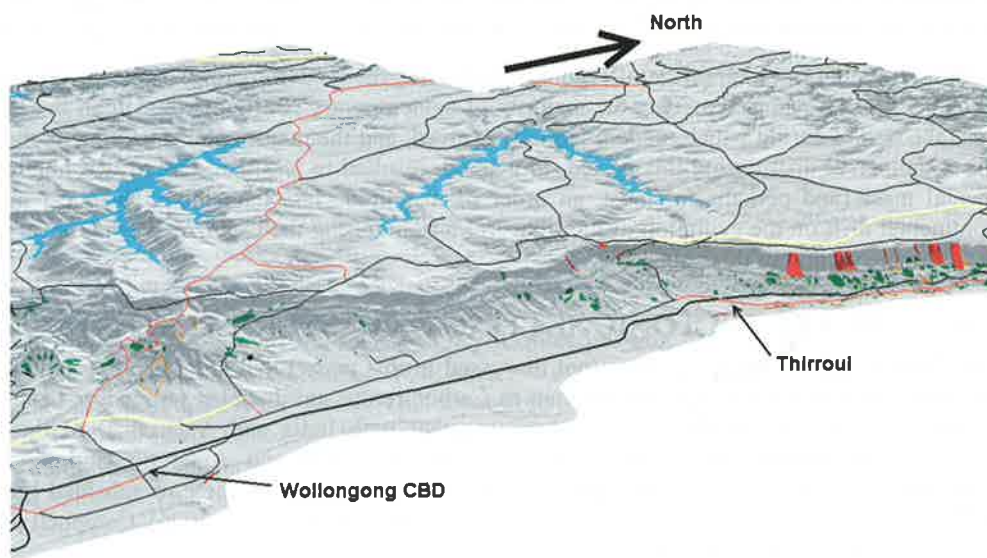


Figure 1: Oblique view to the northwest over a hillshade model of the Illawarra Escarpment and coastal plain between Mount Keira and Austinmer area showing the Landslide Inventory and major road and rail infrastructure and the major catchment dams on the Hawkesbury plateau to the west of the escarpment.

The escarpment consists of slopes with moderate to steep inclinations ( $25^{\circ}$  –  $40^{\circ}$ ) with several intermediate benches ( $-2^{\circ}$  –  $10^{\circ}$ ) and cliff lines. The escarpment comprises a geological sequence of essentially flat-lying interlayered sandstone, mudstone and coal of the Illawarra Coal Measures, overlain by interbedded sandstones and mudstones/claystones of the Narrabeen Group. Spectacular cliffs of Hawkesbury Sandstone (of Middle Triassic age) cap the escarpment and there is dense vegetation over most of the escarpment below these cliffs. The escarpment slopes and the temperate maritime climate with relatively high rainfall levels present a number of challenging hazards for the 9<sup>th</sup> largest city in Australia. It is, therefore, of great importance to understand the evolution of this iconic landscape and the processes that are currently acting upon it.

## 2 THE ILLAWARRA GEOLOGY AND LANDSCAPE'S TIME AND AGE

Throughout this paper, relevant periods of geological time are highlighted and the writer considered it would assist readers to have on hand an overview of the earth's geological time scale. The Earth's 4.6 billion year history is illustrated diagrammatically in Figure 2. The second and third timelines are each subsections of the preceding timeline. The main features of this are the Precambrian Supereon, and the most recent 550 million year Phanerozoic Eon. The middle timeline represents this Phanerozoic Eon, which includes the late Paleozoic and early to mid Mesozoic Permian to Jurassic period. It was during this time interval that the sedimentary sequence of the Sydney Basin which is exposed within the Illawarra was deposited. The bottom row of Figure 2 represents the Cenozoic Era. This is widely recognized as the beginning of the 'modern global' period where the continents are beginning to move towards their current positions. It is worth noting that the 'Tertiary Period' is no longer recognized as a formal unit by the International Consortium on Stratigraphy, with its traditional span being divided between the Paleogene and the Neogene Periods.

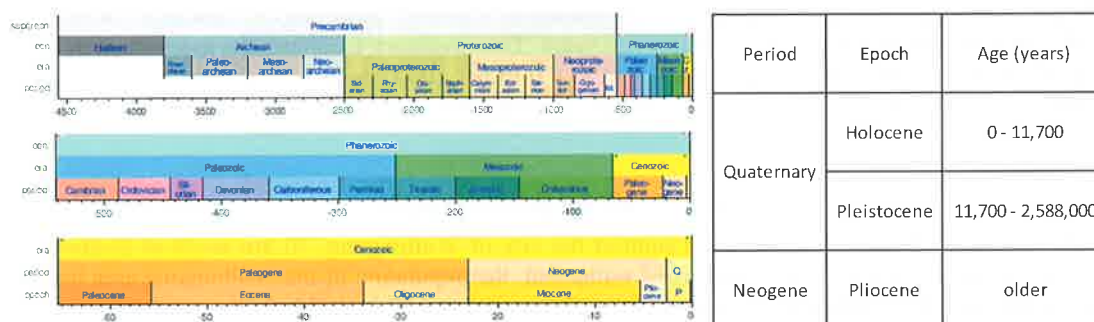


Figure 2: On the left is a graphic timeline of the Earth's 4.6 billion year history subdivided into Supereons, Eons, Eras, Periods and Epochs, sourced from Wikipedia. On the right is the Quaternary Period (from 2.6 Ma), which includes the Pleistocene and Holocene periods. Note the Holocene period as shown here commences 11,700 years before the present as this is the current definition of the Holocene by the International Commission of Stratigraphy (ICS).

The Quaternary Period, on the right hand side of Figure 2, represents the modern period. Major continental geography and topography had generally begun to assume the majority of contemporary configurations, in all but the most active of terrains. This is the period during which modern humans evolved, and the major continents effectively reached their current locations. Continental drift during this period, in general, resulted in less than one to two hundred kilometres drift per continental mass (and perhaps for most, an order of magnitude less than this). The local impact of plate tectonics and continental drift on the evolution of the Illawarra terrain during the Cenozoic Period is very important as discussed in the following section of this paper.

## 3 PLATE TECTONIC SETTING OF EASTERN AUSTRALIA

The Permian and Triassic sedimentary sequences (not discussed in this paper) that comprise the Sydney Basin, were deposited on erosional basement surfaces of the Silurian to Carboniferous age Lachlan Orogen or Lachlan Fold Belt. Australia then represented (Figure 3) the eastern extent (together with India and Antarctica) of the amalgamated Pangaea-Gondwana supercontinent. The eastern margin of the Australian and Antarctic landmass at this time incorporated an additional eastern 500km or so width of land represented in part by the now subsided Lord Howe Rise and Challenger Plateau and the proto New Zealand (Sdrolias *et al.*, 2001, Muller *et al.*, 2006). Campbell (2010) referred to this eastern land mass collectively as Zealandia.

The Sydney Basin formed as part of the regionally extensive Early Permian East Australian Rift System (Korsch *et al.*, 2009) and subsequently as a mid-Permian to Late Triassic foreland basin system that developed in front of the accreting New England Fold Belt. The rift and foreland basin system, which includes the Sydney, Gunnedah and Bowen basins, stretched from southeastern Queensland to south-central New South Wales. It is likely that the basin system extended even further south with basin relicts preserved in the rifted continental fragments that now underlie the southern Lord Howe Rise region.

The opening of the Tasman Sea Basin, and therefore the onset of the development of the eastern Australian continental margin, commenced approximately 90 Ma to the southeast of Tasmania, at about the same time as the onset of rifting between Australia and Antarctica. The opening of the Tasman Sea Basin was moderately complex as it essentially unzipped the current eastern Australian margin from north to south. Reconstructions (Gaina *et al.*, 1998, Sdrolias, *et al.*, 2001 and Muller *et al.*, 2006) have traced the relocation of up to 13 micro-plates off the eastern Australian coast (Figure 4). The rifting of the continental margin and opening of the Tasman Sea is considered to have occurred in the Sydney region around 70 million years ago and this sets the framework for the subsequent development of the escarpment terrain. Since then, the southeastern continental margin is considered to have remained relatively unchanged with the exception of minor ongoing subsidence due to thermal cooling after the cessation of the rifting.

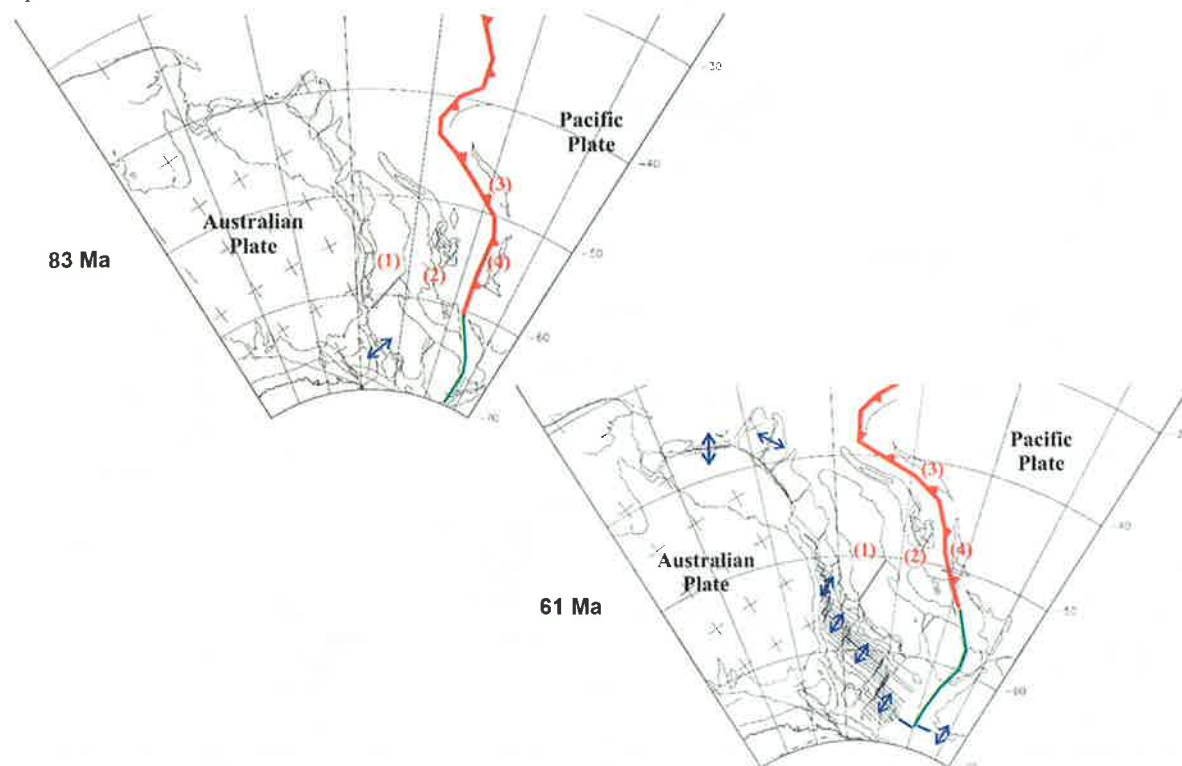


Figure 3: Two reconstructions (stereographic projection) for the region east of Australia representing the eastern portion of Gondwana at 83 and 61 Ma in an absolute reference frame. The numbers 1 to 4 in each image refer to the Micro Plates (1) = Lord Howe Rise, (2) = Norfolk Ridge, (3) = Loyalty Ridge, (4) = Three Kings Ridge. Red solid lines denote the subduction zone, with the triangles pointing to the direction of subduction, blue arrows denote rifting and direction and solid black lines denote isochrones (Sdrolias *et al.*, 2001).

This review of the work of others concerning the plate tectonic setting of this region almost completes the picture for the Sydney Basin region from before the time of deposition of the Sydney Basin up to the early Paleocene. The implications for global climate are discussed later in this paper. The supercontinents of Pangea and then Gondwana implicate completely different ocean circulation and therefore climatic settings. One other plate tectonic reconstruction is also useful to further this discussion and relates to the absolute position of the Australian landmass on the globe in relation to the poles. One such interpretation (Vasconcelos *et al.*, 2008) is shown in Figure 5. The latitude of Wollongong today is approximately 34° South. This reconstruction shows that Australia maintained a position at high latitudes for much of the Early Cenozoic, before rapid sea-floor spreading occurred between the two continents of Australia and Antarctica, commencing around 55 Ma, and this resulted in a rapid migration of Australia into tropical and sub-tropical latitudes. This movement continues today, with the Indo-Australian plate still moving to the north at approximately 7cm per annum (Quigley *et al.*, 2009).

#### 4 LATE QUATERNARY SEA LEVEL HISTORY

Sloss *et al.*, 2007 provide a comprehensive summary of Quaternary climate variability. They also discuss more recent sea level findings for south eastern NSW and, importantly, some possible reasons for the cyclic variability it displays. The sea-level history along the southeastern NSW coastline and continental shelf is important as it has had a profound effect on the geomorphological evolution of the local coastline known today.



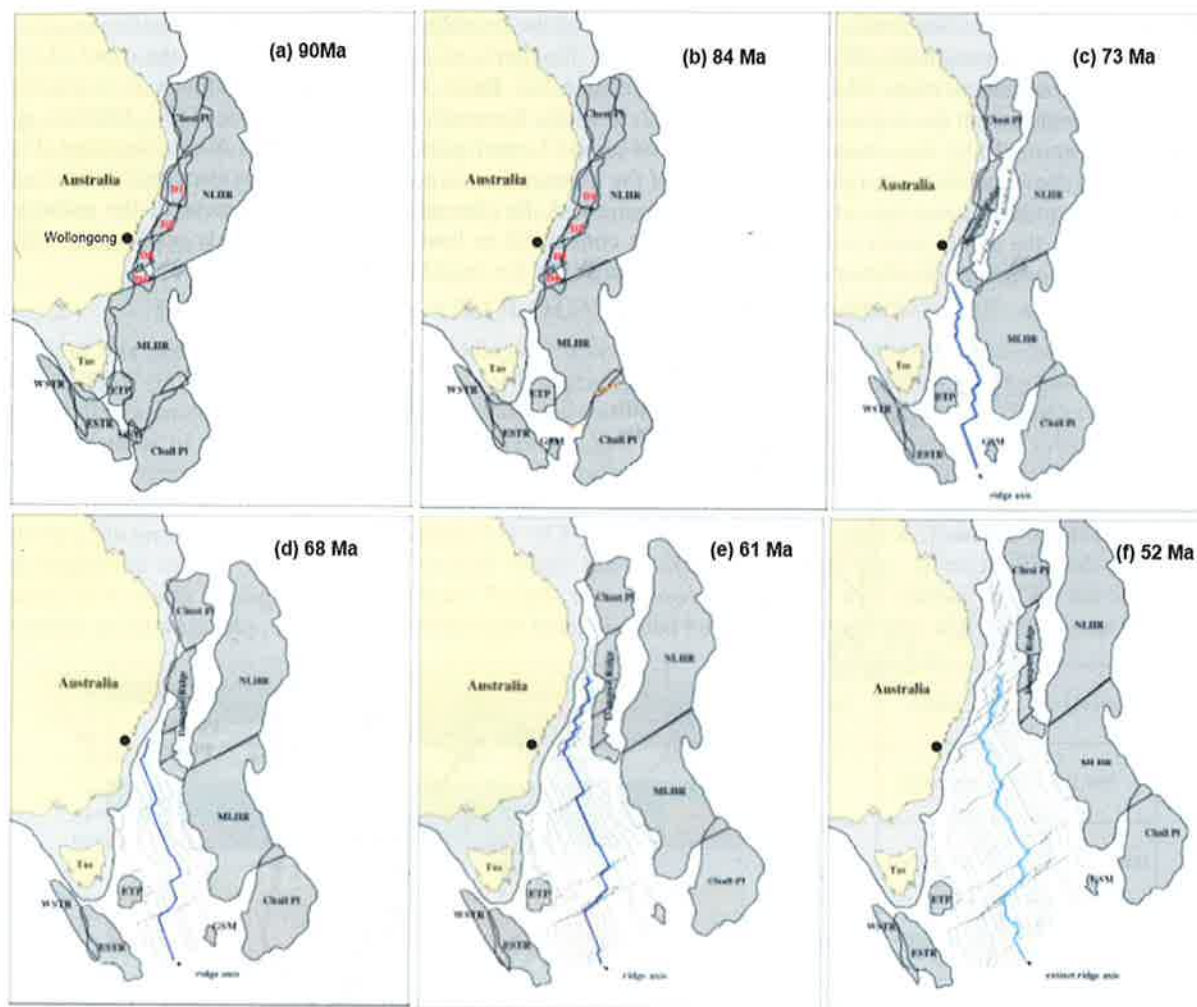


Figure 4: Compilation of figures from Gaina *et al.*, 1998 and highlighting the location of Wollongong. (a) The tectonic setting of eastern Australia with the 13 micro plates involved in the opening of Tasman Sea is shown in the first figure at approximately 90 Ma. Initialised blocks include: NLHR and MLHR, the north and middle Lord Howe Rise; Chall. Pl., the Challenger Plateau; STR, the South Tasman Rise; and the ETP, the East Tasman Plateau, (b) The micro plates position at approximately 84 Ma, (c) at approximately 73 Ma and here rifting is shown to have commenced in the vicinity of the Illawarra region, (d) at approximately 68 Ma and sea floor spreading is well advanced of the Illawarra coastline, (e) at approximately 61 Ma when spreading slowed and (f) at approximately 52 Ma when the current configuration of the Tasman Basin has been reached and spreading effectively ceased.

Gordon (2003) published a summary paper on this topic focussed on the Perth area and much of it is directly relevant (perhaps bar the precise specific sea levels) to the NSW southeastern coastline. The Quaternary was characterised by cycles of alternate cold and warm periods that produced glacial and interglacial stages. The cyclical nature of the fluctuating climate is clearly shown in Figure 6 over the last 720,000 years by the temperature variations interpreted from the changing oxygen isotope content of pelagic foraminifera from deep-sea cores (Shackleton & Opdyke, 1973). Several points are worthy of note from this figure;

- Peaks and troughs occur at more or less regular intervals of 100,000 years,
- There is a saw tooth pattern of gradual temperature drop associated with the most pronounced glacial events, followed by a rapid warming to the interglacial maximum temperature, and
- Over a period of 720,000 years the temperature maxima and minima have nearly equal values.

Gordon (2003) and Sloss *et al.* (2007) summarised some possible explanations for these cyclic temperature oscillations suggesting they are associated with mechanisms related to the sun and the earth's orbit (Milankovitch, 1941). These mechanisms include: (a) Eccentricity - the shape of the earth's orbit which varies between elliptical to near circular on a near 100,000 year cycle, (b) Precession - the wobble of the earth's axis (23,000 to 19,000 year cycle) and (c) Obliquity - or axial tilt between 21.5° to 24.5° on a 41,000 year cycle.

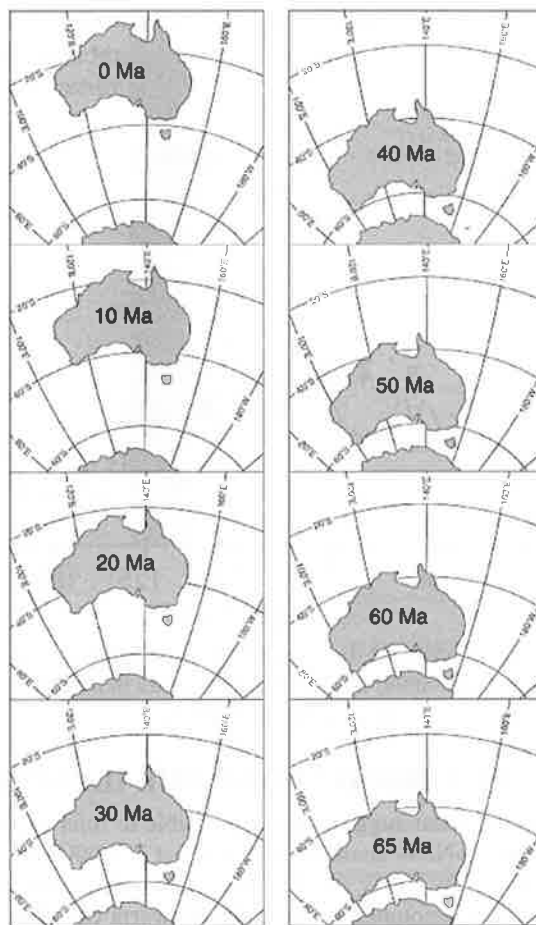


Figure 5: Cenozoic plate reconstructions for Australia and Antarctica (Vasconcelos *et.al.*, 2008) showing the position of Australia at high latitudes for much of the Early Cenozoic, before the fast sea floor spreading between the two continents, commencing around 55 Ma, led to rapid migration of Australia into tropical and sub-tropical latitudes.

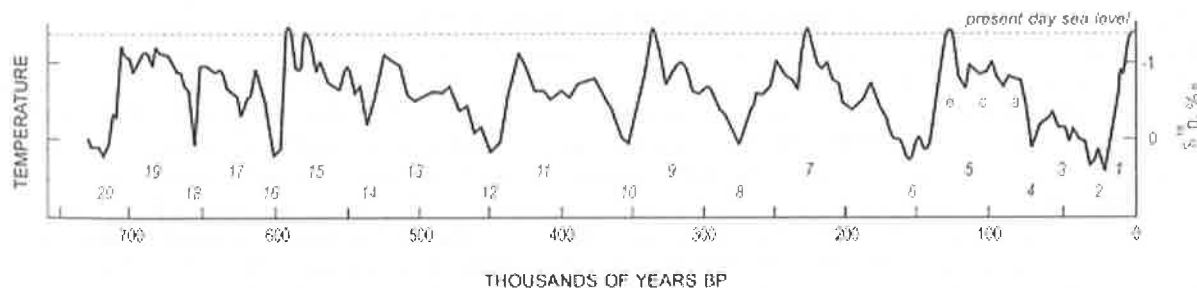


Figure 6: Generalised global relative palaeo-temperature and sea level curve, last 720,000 years (after Shackleton and Opdyke, 1973) from Gordon (2003).

Other effects would also include isostatic changes and thermal change (thermal expansion is predicted to make up around half of the forecast rise to 2100, IPCC TAR).

Oxygen Isotope content of ocean basin pelagic or benthic foraminifera from deep-sea cores have allowed the time lines to be defined as Marine Isotope Stages (MIS) as shown in Figure 7. The current Holocene high stand period being defined as Stage 1. The sea level high stands are known as Interglacial periods, such as we presently experience (Figure 7, MIS 1 and 5 or strictly 5e). The sea level lows are known as Glacials or Glacial Maximums (Figure 7 MIS 2 and 6), when there is a widespread global expansion of continental wide ice sheets and mountain glaciers which is of course accompanied by lower global sea levels. Stadials are colder episodes (Figure 7 MIS 4, 5b and 5d) that are shorter than glacial phases and these are characterised by localised expansion of ice and result in fluctuations of sea level in the order of tens of metres. Interstadials are relatively short episodes of warming within a glacial phase (Figure 7 MIS 3, 5a and 5c) and these also result in fluctuations of sea level in the order of tens of metres or so.

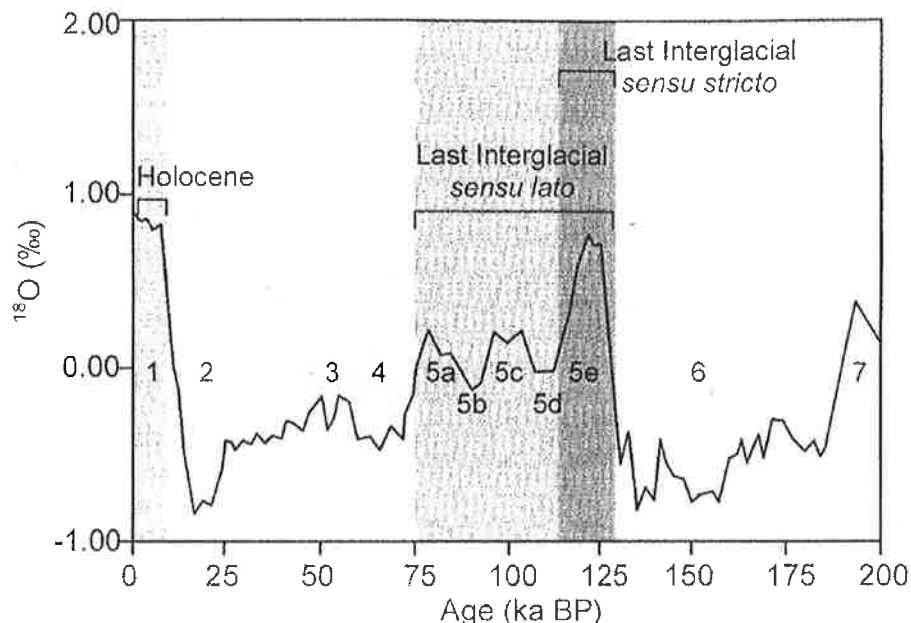


Figure 7: Marine Isotope Stage (MIS) record over the last 200,000 years (Sloss *et al.*, 2007). The current high stand is referred to as MIS 1, and the previous High Stand approx 125,000 years before the present is referred to as the MIS 5, or specifically MIS 5e.

## 5 THE HOLOCENE PERIOD ALONG THE ILLAWARRA COASTLINE

In the absence of better information, the writer suggests it is acceptable to refer to Figures 6 and 7 as representative of the sea level history along the southeastern NSW coastline over the last 720,000 years. Figure 8 is a modified version of a figure from the aforementioned paper by Sloss *et al.*, 2007 which discusses Holocene sea-level change on the southeast coast of Australia. This work was completed along the Illawarra coastline and the average rates of sea-level have been annotated on the figure by the writer. The source paper includes another figure showing even more detailed variation (far from steady state) during the recent high stand period.

The steep rising sea-level curve on the left side of Figure 8 is the last three thousand years of the approximately 15,500 year global marine transgression after the latest glacial maxima (MIS 2). This curve represents an approximately 130 m rise plus an additional 1.5 m above today's level, which is equivalent to a 0.85 m sea level rise every 100 years, sustained for 15,500 years. No doubt during this time the rates would have been quite variable, perhaps even receding at times, but also perhaps even half or one order of magnitude higher at times. Then, from the period 7,500 years before the present (bp) to approximately 2,000 years bp, a relatively stable period ensued whereby sea-level was maintained at approximately 1.5 m above present levels. The data indicates variability during this period (Figure 6 in Sloss *et al.*, 2007) but nonetheless maintained a positive level from approximately 5,500 years. Then from approximately 2,000 years bp, the sea level dropped from the 1.5 m level to its present level. This fall occurred at a rate of approximately 75 mm per 100 years. Interestingly, the DECCW 2009 projection for coastal NSW is a rise of 0.9 m by 2100, a rate of 10 mm per year. This rate is about the same as the rate experienced during the last post glacial maximum rise, albeit to a level lower than the 1.5 m or so level above the present level that was sustained for more than half of the last 10,000 years.

## 6 CENOZOIC EVIDENCE OF CLIMATE VARIABILITY

Quaternary palaeoclimatic research over the last few decades has clearly identified that global climate variability has been dramatic. Goudie (2006) states that the degree, frequency and abruptness of changes during the Quaternary have been 'remarkable'. A dominant event during the Cenozoic has been the Paleocene Eocene Thermal Maximum (PETM) and subsequent Cenozoic climate/thermal decline (Figure 9).

Peaks and troughs (global temperature, sea level etc), reaching similar magnitudes, occur at more or less regular intervals of 100,000 years. Nanson *et al.*, 2003 has shown during the past 300,000 years (three glacial cycles) that Australia passed through a sequence of dry and wet episodes associated with the global glacial cycles during the Mid to Late Quaternary. However, superimposed on these oscillations has been a progressive drying trend over this period. The northern inland rivers are now only a vestige of their pre-Holocene condition. The Holocene appears to represent an

extraordinarily dry interglacial, quite unlike the past two interglacials, and significantly drier than the last interstadial (Stage 3).

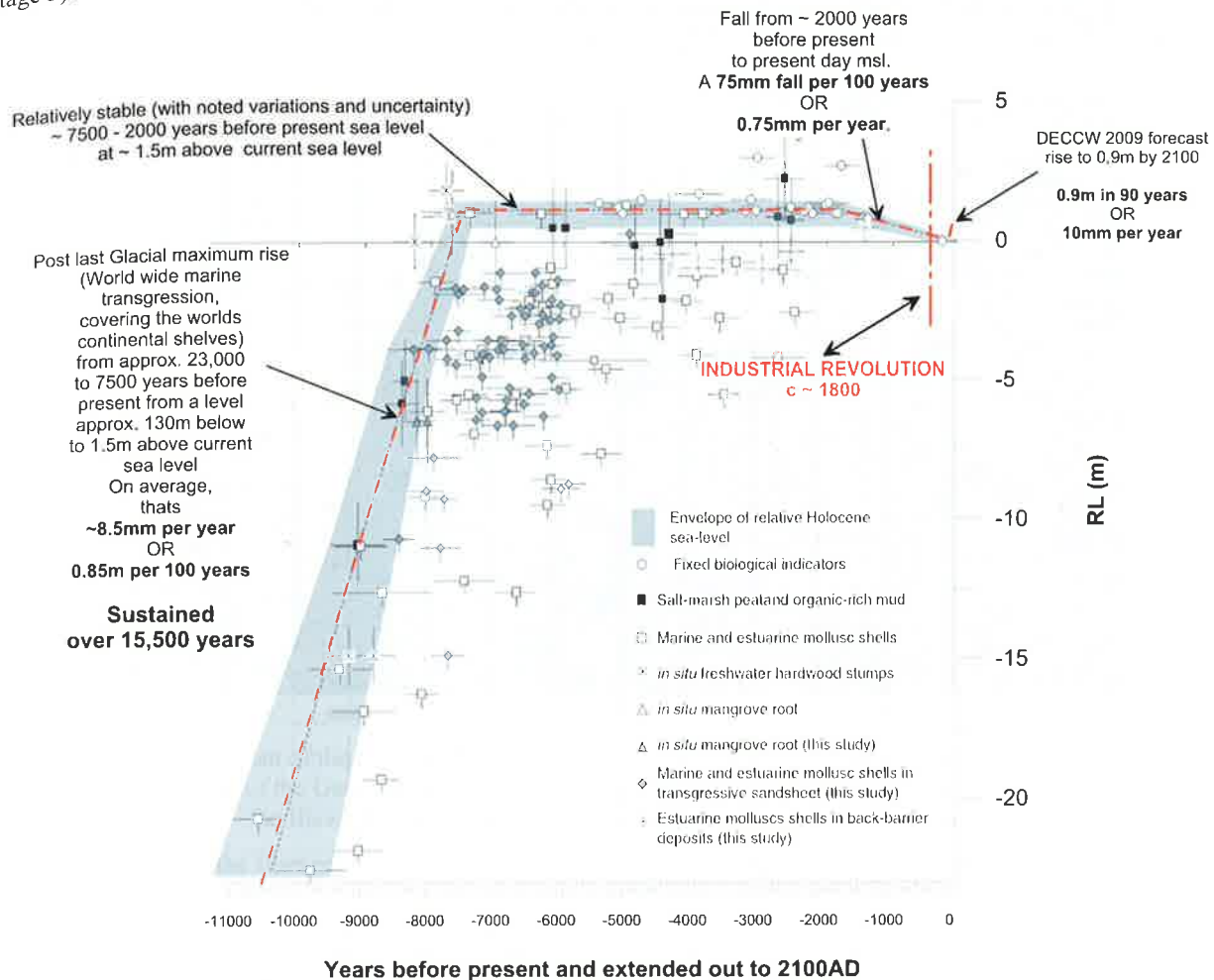


Figure 8: Modified revised Holocene sea-level curve for the southeast coast of NSW based on previously published radiocarbon ages calibrated to sidereal years, radiocarbon ages obtained for this study and aspartic acid racemisation-derived ages. The shaded area representing the envelope of relative Holocene sea-level rise based on the synthesis of previously published data and new data obtained in the Sloss *et al.*, 2007 study. Flentje has calculated 'average' rates of sea level change as reported on the figure.

Landscapes form as a result of the interaction between climate, weather, topography, geology and the surface processes. Therefore, the landscapes and the associated subsurface materials that we now see may in all likelihood have been inherited from climatic conditions significantly different from those experienced today. Goudie (2006) noted that such 'legacy' landscapes are common. Fundamental principles at the core of geology, that of uniformitarianism and one of Lyell's (1830) core guiding principles that the 'present is the key to the past' may not strictly hold entirely as expected for such legacy terranes and associated deposits. This has implications for hazard triggering events and the assessment of recurrence periods.

Nott (2003) noted the potential for hazard regimes temporally and in northern Queensland noted a substantial regime shift in landslide activity related, in this instance, to the last glacial maxima, such that only landslides from the last 10,000 years should be assigned to the current hazard regime locally when considering a risk assessment for this hazard. The implications of the presence of such legacy landscapes incorporating deep weathering profiles, basalts, laterites, silcretes, evaporates, periglacial deposits, colluviums etc and all of the associated surface processes should be considered with this in mind. The existence of such legacy landscapes has important implications for the assessments of current process rates and the assessment of frequency today, particularly if the relevance of such legacy features is not recognised.

The sea level fluctuations have a number of important implications for coastal development. Currently the sea levels are at or near the highest levels they have been globally, certainly over the last million years or so. During glacial peaks however, sea levels have been up to approximately 130m lower. During these times, rivers will have eroded and



scoured channels, extensively in some locations, to greater depths and potentially up to 130m lower than today, to reach the coastline at that time. During the marine transgressions, these eroded valleys become inundated and infilled with fluvial and/or marine deposits. This process has occurred up to ten times in the last million years and, in all likelihood, many more before that.

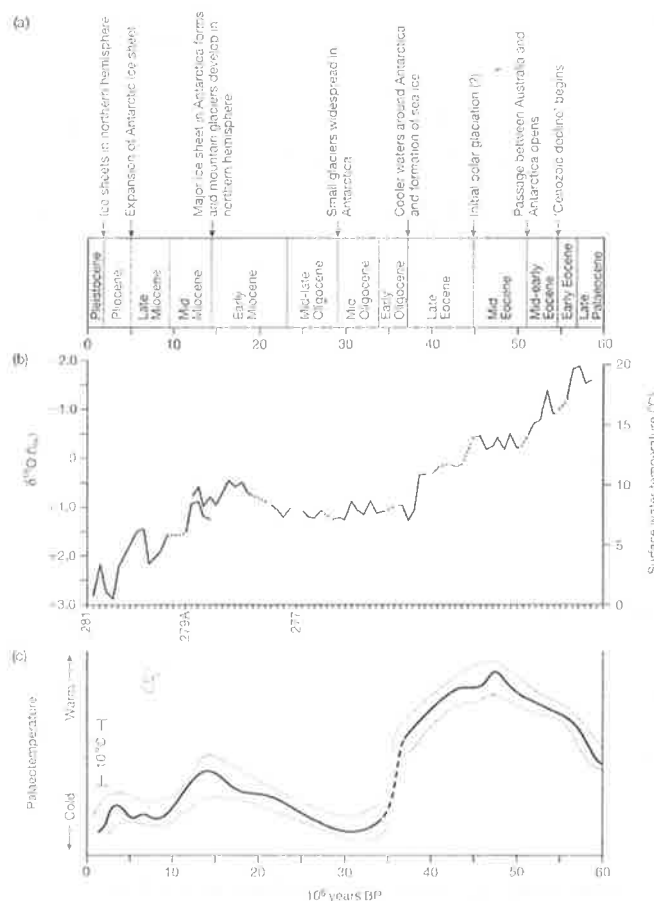


Figure 9: The Paleocene Eocene Thermal Maximum (PETM) and subsequent Cenozoic climate decline (a) The upper timeline outlines significant events in the Cenozoic climate decline (b) Oxygen isotopic data and palaeotemperature at three sub-antarctic sites and (c) temperature changes calculated from Oxygen isotope values of shells in the north sea (Goudie, 2006).

During the Interglacials, and particularly during the recent highstand from 7,500 to 2000 years before present, lagoonal type environments developed immediately inland from many coastal areas on low lying coastal plains. Swamp type environments would have developed along the flood plains of the coastal rivers. Many of these areas today are potential acid sulphate soil (PASS) type environments. It is also during these Interglacial high stands when erosion rates on the escarpment may have been at their relatively highest levels due to the proximity to the coastline and the effects on the slopes above from the marine transgressions, subject to the climatic variability of the time.

## 7 THE ILLAWARRA TERRAIN

The sea level variations discussed in the previous section have been acting on this coastline for at least the last 30 million years, and possibly up to 70 million years. It is clear from the preceding discussion that there is some understanding of this process over the last 1 million years and an even better understanding of at least some of the processes in the last 10,000 years or so.

With the aid of the Geoscience Australia's 250 m pixel size Australian Bathymetry and Topography Grid (2009) as shown in Figure 10, a moderately detailed regional cross section of the Illawarra Continental margin has been prepared, as presented in Figure 11. This section extends from north of the Picton Area east to the coastline near Stanwell Park and then out across the continental shelf and slope and into the Tasman Basin. Figure 11 extends over 180 km, covers a vertical relief of 5,500 m and employs a 10 times vertical exaggeration.

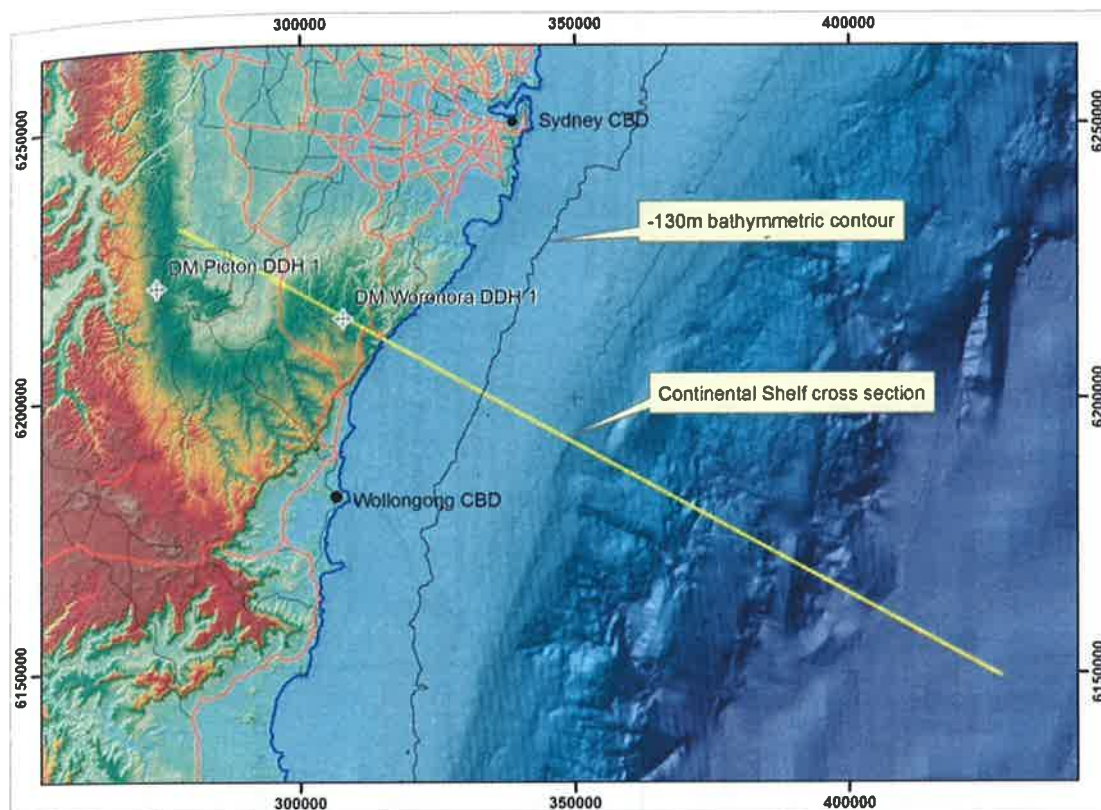


Figure 10: Location plan of the continental shelf and slope cross section as shown in Figure 11. Using the ESRI ArcGIS hillshade model of the Geoscience Australia 250 m pixel size Australian Bathymetry and Topography Grid of the Illawarra region. The -130 m bathymetry contour is also shown.

Figure 11 depicts that the Illawarra Escarpment has evolved as a result of the natural processes of escarpment retreat and associated slope processes, coastal erosion and marine abrasion which have collectively removed the shaded coastal wedge area. Figure 11 shows the Continental Shelf in the vicinity of the Illawarra as being approximately 40 km wide. Since the rifting commenced around 70 million years before the present, coastal erosion and slope retreat along this margin of the Tasman Basin has resulted in this locally 40 km wide continental shelf. This provides a long term average process rate for the coastal erosion and slope retreat of 40 km divided by 70 million years, 0.6 m per 1,000 years, or 0.6 mm per annum.

Basin subsidence occurred during the accumulation of the Sydney Basin sediments. The Illawarra Plateau and the Woronora Plateau descend to the north as a result of this regional dip. The Illawarra coastal plain, as a result of this structurally controlled dip has been inundated to the north and at least in part been submerged and partially removed by coastal erosion and marine abrasion during the Cenozoic marine transgressions (induced in part by the post rifting thermal cooling). As a result, the escarpment north of Thirroul (where the coastal plain has been inundated) is being undercut by direct coastal erosion and marine abrasion. The result is that the escarpment here is presently oversteep, as evidenced by the presence of the steep slopes and coastal cliffs north of Thirroul. Whilst the escarpment has widespread landsliding, there is an acute increase in landslide density on the escarpment slopes north of Thirroul (see Figure 1). This is also exacerbated by an increase in urban development higher up on these slopes north of Thirroul.

Using a similar logic, Thom *et al.* (2010) in discussing the East Australian Marine Abrasion Surface (Figure 12) concluded an average rate of cliff retreat of 1 mm per annum, although they acknowledged this could vary between 0.4 and 2 mm per annum. This estimate was based on a more detailed model than the writer had access to, including an outer shelf sediment wedge age of Mid Oligocene (30 million years) and a continental shelf width to the on-lapping edge of this wedge of 30 km. Both models, however, provide similar retreat rates.

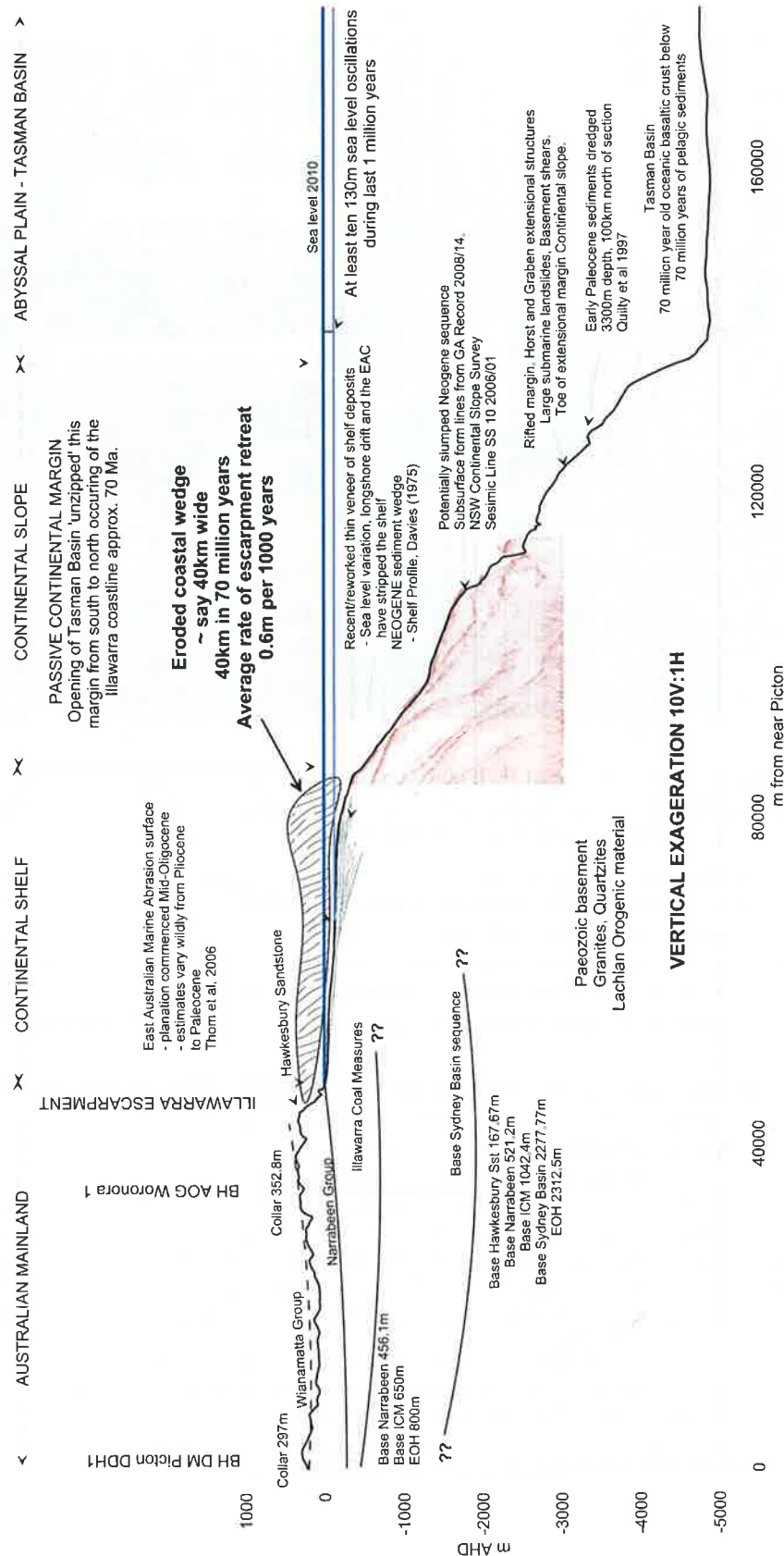


Figure 11: Continental shelf cross-section from the Picton area, through the escarpment near Stanwell Park and out into the Tasman Basin abyssal plain. Current sea level is shown, as is the ~130 m variation that occurs between successive Glacial maxima and Interglacial high stands (such as today). The cross-section shows the geometry of the eroded coastal wedge that has been used to determine the average 0.6m per 1000 year retreat rate.

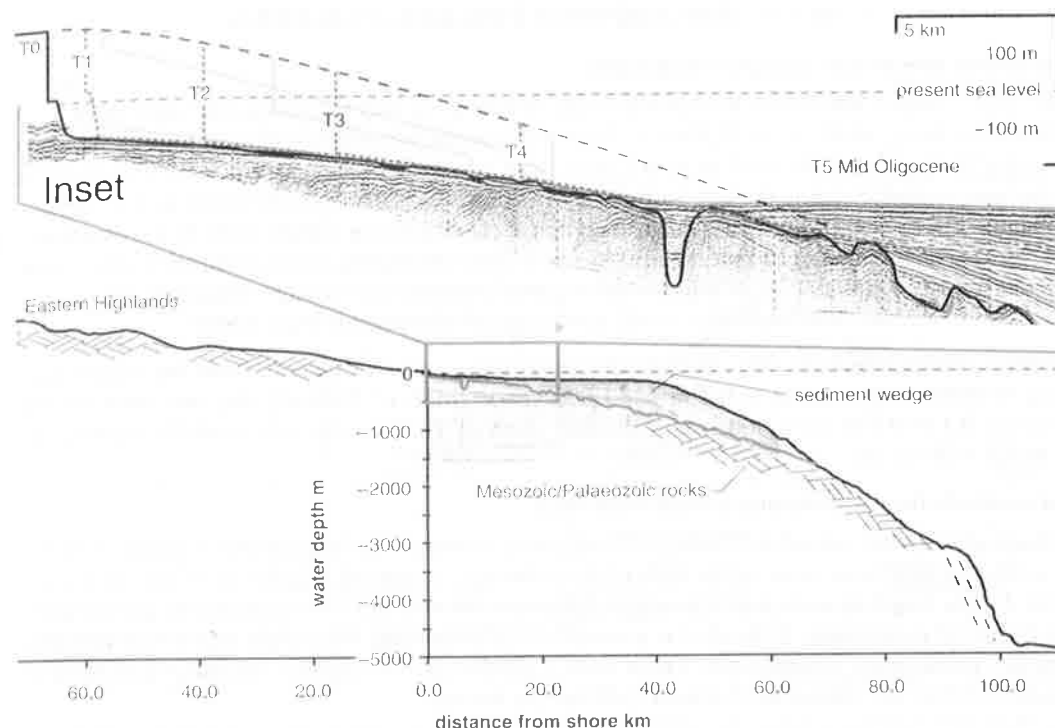


Figure 12. Thom *et al.*, 2010 discussed the East Australian Marine Abrasion Surface with this section of the continental shelf, which includes an incised and backfilled Hawkesbury River channel. Thom *et al.* concluded a rate of retreat  $\sim 1$  mm per annum, but acknowledged variability within the range 0.4 – 2 mm per annum.

## 8 CONTEMPORARY SLOPE INSTABILITY ON THE ESCARPMENT

In addition to alluvium, almost all of the escarpment surface, apart from the cliff lines, steep spurs, coastal rock shelves and deeply incised watercourses, is covered by significant accumulations of colluvium. The colluvium comprises a mix of rocky debris with some extremely large boulders and smaller fragments derived from the sandstone, mudstone, siltstone and coal units. This coarse material is supported in a matrix of sands and clays and is derived from the Hawkesbury Sandstone, Narrabeen Group formations and the Illawarra Coal Measures. The colluvial material is associated with active contemporary landsliding on the escarpment. Slope instability is a significant hazard for urban development and associated infrastructure on the escarpment terrain. Stone (2012) discusses the specific mechanisms of instability at specific locations along the escarpment in association with the South Coast Railway. Tobin (2012) discusses the management and costs to local government associated with landslide remediation at three specific sites on the escarpment. Leventhal and Flentje (2012) present four Illustrative Escarpment Sections depicting geology and separately Landslide Susceptibility. These three papers are companions to this paper and appear elsewhere in this edition.

Today, processes and mechanisms of slope instability are controlled on the Illawarra Escarpment by factors that include: the local geology and its stratigraphy, the geotechnical strength parameters of the bedrock material and their derivatives of alluvium and colluvium, the discontinuities in the bedrock mass (including faults, dykes and joints etc), hydrogeology, geomorphology, slope inclination, rainfall, pore water pressure and the actions of man.

The Wollongong regional Landslide Inventory, which has been developed over the last 20 years, currently contains 665 landslide locations with a total of 1,050 landslide events (including first time occurrences and multiple recurrences at some sites). This is managed with the aid of a relational MS Access and an ESRI ArcGIS<sup>TM</sup> Geodatabase with over 70 fields of information for each landslide site (Flentje and Chowdhury, 2005, Flentje *et al.*, 2011). Field mapping and desktop compilation work has been carried out on field maps and using GIS software at 1:4000 or larger scales. Each landslide is referenced by the key Site Reference Code (SRC). Some of these landslides are shown in Figure 1, albeit at small scale.

The 665 landslides comprise 43 Fall, 79 Flows and 462 Slide category landslides according to the Cruden and Varnes (1996) classification. In addition, there are several scour related sites and a few sites that have not been classified. A total of 595 landslides are located within the 545 km<sup>2</sup> Wollongong Council Local Government Area and volumes have been determined for 493 of these sites. The volumes range from  $<1$  m<sup>3</sup> up to 720,000 m<sup>3</sup>, with an average volume of 18,800 m<sup>3</sup> (please note these reported numbers do vary with time as the inventory develops, grows and is refined).



## 9 ESCARPMENT RETREAT RATES

### Escarpment retreat due to slide category landsliding

A total of 393 slide category landslides, located within the Wollongong City Council Local Government Area inventory have an estimated volume, which is 8,615,000 m<sup>3</sup>. Each event in the Inventory is assigned a date if known. When the inventory timeline is considered, 99 % of the data is post 1950, and 80 % of the data is post 1989, so it is clear that most of the data has been recorded during the last 30 years. The following judgements are based on this 30 year period. It is recognised that the known number of landslides is incomplete (landslides on remote areas of the escarpment will exist) and the number of actual events (recurrences) at each site is also incomplete, hence subjective adjustments have been made to account for this. One final set of judgements required concerns the average magnitude of event displacement, and an assessment of how far these landslides would need to travel to represent slope retreat.

These judgements, whilst subjective, have been made based on the writer's experience and the assessed average rate of slide category landslide slope retreat is 0.2 m per 1,000 years. North of Thirroul, this rate could be expected to be higher, at perhaps 0.3 to 0.5 m per 1,000 years, whereas, south of Thirroul, this rate could be expected to be lower at perhaps 0.1 m per 1,000 years.

### Escarpment rockfalls from Hawkesbury Sandstone cliffs

The total volume of non-mine subsidence induced Hawkesbury Sandstone failures in the inventory is 80,740 m<sup>3</sup>. On the basis of the estimated recurrence interval for each of these failures, an annual supply rate of Hawkesbury Sandstone of 644 m<sup>3</sup> for the 55 km length of escarpment mentioned above is determined. This indicates an annual supply rate of 10 m<sup>3</sup> per 1 km length of escarpment. If the cliff is assumed to be on average 40 m high then it will retreat at an average rate of 0.3 m per 1,000 years. Interestingly, Kotze (2007) reported a Hawkesbury Sandstone and Newport Formation rockfall volume of 10 m<sup>3</sup> per kilometre of coastal cliff-line per annum.

### Bald Hill Claystone and Bulgo Sandstone slope rate of retreat due to debris flows

During the August 1998 event a series of approximately 30 small debris flows occurred on the Bulgo Sandstone slopes near Bulli Pass. Based on an estimated average source volume (for each one of these debris flows) of 200 m<sup>3</sup> the estimated total volume of these failures is 6,000 m<sup>3</sup>. This series of debris flows occurred as the result of a well documented > 1:100 year 6-hour peak intensity event. A corresponding rate of loss over 1,000 years could be 60,000 m<sup>3</sup>. The Bulli Pass debris flows occurred over an escarpment length of 1300 m and extended down slope over a length of up to 335 m, covering an area of 435,500 m<sup>2</sup>. This suggests a Bald Hill Claystone and Bulgo Sandstone slope retreat rate of 0.14 m per 1,000 years due to debris flows alone. Clearly, this rate would be higher if other colluvial processes, such as sliding and alluvial slope wash processes were to be included.

### Lawrence Hargrave Drive (LHD) Process Rates

Following a detailed literature review, field investigations and a comprehensive interpretation of the evidence on the geological and geomorphological history of the region and project area (including some earlier iterations of some of the escarpment retreat rates mentioned above), a slope retreat rate model was developed for the Lawrence Hargrave Drive Project (Moon *et al.*, 2005). This site is situated in the northern Illawarra Escarpment slopes, in an over-steepened area of the escarpment. Figure 13 summarises the average slope retreat rates (in m per 1,000 years) for a range of different slope units above the road.

### Delaney (2005) reported cliff line retreat rates from Newcastle

In a comprehensive review of coastal cliff line recession rates in the Newcastle area, Delaney (2005) reported a range of rates from 1 to 40 mm per year (with one value up to 80 mm per year possibly related to mine subsidence). These rates were based on survey data, historical records, photographs and various assumptions of cliff morphology over the last 150 years. Such rates are probably realistic in shorter term annual or even hundred year type scenarios, including retreat resulting from individual fall events at specific locations.

### Summary of Retreat Rates

The rates of escarpment retreat discussed above are summarised in Table 1 and displayed graphically in Figure 14. Both Table 1 and Figure 14 contain additional data that has not been discussed in this paper. This additional data is referenced and interested readers are directed to these references as required. Figure 14 clearly demonstrates that this data set spans 5 orders of magnitude. However, the majority of the retreat rates discussed above and which are based on contemporary Illawarra data, all lie within one order of magnitude, from 0.1 to 1 m per 1000 years and most actually fall within half this order of magnitude. The narrow spread suggests they may also be in the right ballpark. However, several of the values from Moon *et al.*, 2005 are in the higher range of 2 and 3 m per 1000 years. This is possible given the relatively high erosion rates clearly demonstrated along the coast in the cliff lined amphitheatres spanned by the Seacliff Bridge works. The 1 to 40 mm per year figures reported by Delaney (2005) appear to be not sustainable over

longer periods of time. The writer suggests the longer term (1000 year) process rates are likely to be in the lower order of this range, at the highest.

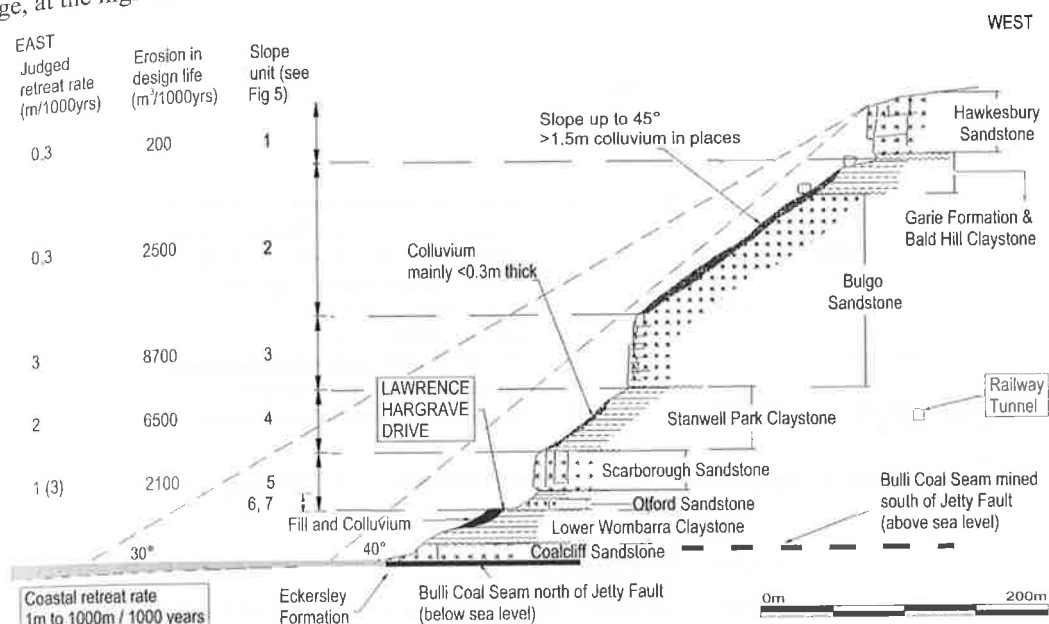


Figure 13. Cross section of coastal escarpment at Lawrence Hargrave Drive showing slope units and slope retreat rates (from Moon *et al.*, 2005, Figure 4).

Table 1. Summary of retreat rates presented in the discussion above and also two denudation rates. (Tomkins *et al.*, 2007)

Retreat Rates		Geological Unit	Project	Authors
mm/year OR m/1000 years	Volume m <sup>3</sup>			
0.6		Regional cross section	Illawarra Escarpment	Flentje, 2012
1		Regional cross section	Southeast coastline	Thom et al, 2006
depends on height of cliff	10	Hawkesbury Sandstone, Newport Formation	Rockfall, Pittwater area	Kotze, 2007
0.3	10	Hawkesbury Sandstone	Rockfall, Illawarra Escarpment	Flentje, 2012
0.2		Narrabeen Group and Illawarra Coal Measures	Slide category landslides	Flentje, 2012
0.14		Bald Hill Claystone and Bulgo Sandstone	Debris flows, August 1998, Bulli Pass	Flentje, 2012
0.3 to 3		Oversteepened Narrabeen Group units	Lawrence Hargrave Drive, Coalcliff to Clifton	Moon et al, 2005
1 to 40		Narrabeen Group units	Newcastle coastal cliffs	Delaney, 2005
0.0055 ± 0.004 to 0.0215 ± 0.007		Hawkesbury Sandstone Upper Narrabeen Group	Western Blue Mountains, NOT including mass wasting	Tomkins et al, 2007
0.012 to 0.025			Sassafrass Plateau	Young & MacDougall, 1985
1			Humid Temperate climate	Young, 1972
0.04 to 0.25		Hawkesbury Sandstone	local reports of Clifton Boulder recurrence	Tobin and Flentje, anecdotal

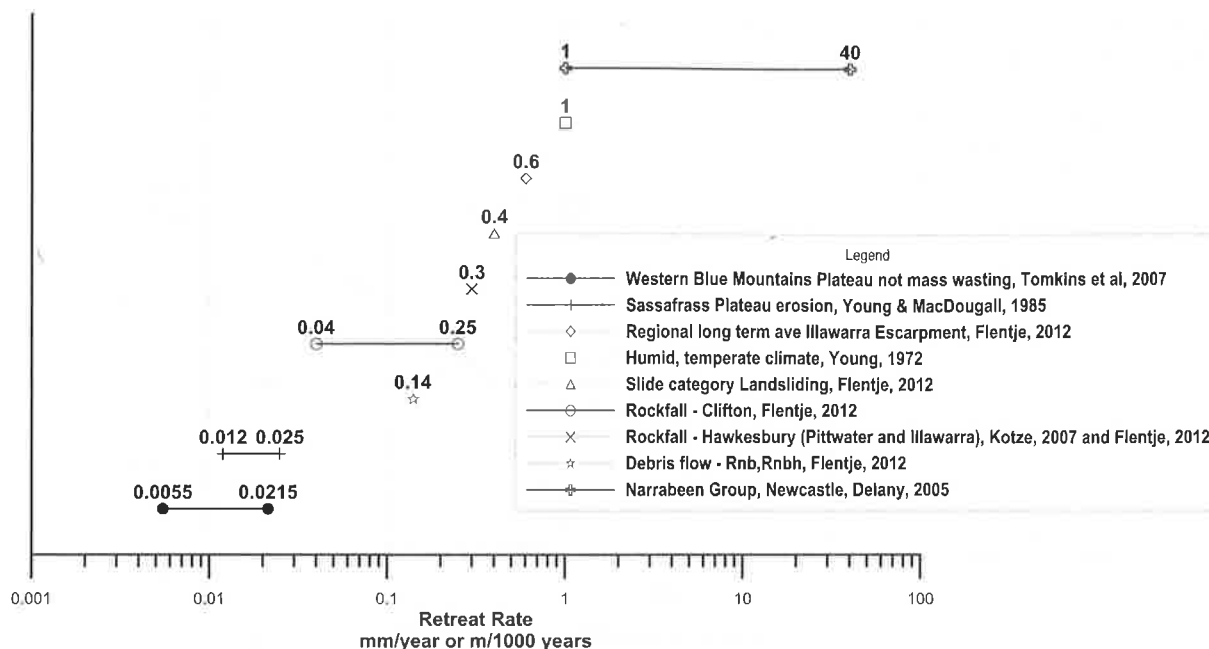


Figure 14. Retreat rate summary, showing all the retreat rates in Table 2.

## 10 SUMMARY AND CONCLUSIONS

The Sydney Basin formed as part of the regionally extensive Early Permian East Australian Rift System (Korsch *et al.*, 2009), and subsequently as a mid-Permian to Late Triassic foreland basin system that developed in front of the accreting New England Fold Belt. The Permian and Triassic sedimentary sequences that comprise the Sydney Basin were deposited on erosional basement surfaces of the Silurian to Carboniferous age Lachlan Orogen or Lachlan Fold Belt.

The opening of the Tasman Sea Basin unzipped the current eastern Australian margin from north to south. The rifting of the continental margin and opening of the Tasman Sea is considered to have occurred in the Sydney region around 70 million years ago and this sets the framework for the subsequent development of the escarpment terrain. Since this time, the southeastern continental margin is considered to have remained relatively unchanged tectonically with the exception of minor ongoing subsidence due to thermal cooling as the rifting progressed and after the cessation of the rifting.

A dominant event during the Cenozoic has been the Paleocene Eocene Thermal Maximum (PETM) and subsequent Cenozoic climate/thermal decline. Quaternary palaeoclimatic research over the last few decades has clearly identified that global climate variability has been high. Goudie (2006) states that the degree, frequency and abruptness of changes during the Quaternary have been pronounced. Nanson *et al.*, (2003) has shown a progressive drying trend over the last three glacial cycles (300,000 years). The Holocene appears to represent a particularly dry interglacial, quite unlike the past two interglacials, and significantly drier than the last interstadial. If this trend was experienced in the Illawarra, the scale of landsliding on the escarpment during the previous two Interglacial periods may have been larger than during the Holocene period. It may be expected then that the rate of escarpment retreat may fluctuate much like the Oxygen Isotope/Sea Level curves. Current rates of retreat could be expected to be relatively high in the current Interglacial, perhaps at 0.5 m up to 2 m per 1,000 years, whilst they may drop, perhaps to 0.05 m to 0.2 m per 1000 years, during the Glacial periods. These rates will of course be varied by not only climatic factors such as discussed by Nanson *et al.*, (2003) but also by the distance of the coastal interface to the escarpment slopes.

The Illawarra Escarpment has evolved as a result of the natural processes of escarpment retreat including slope instability, coastal erosion and marine abrasion. Slope instability and landsliding are considered to be the dominant erosional slope process, although scouring is important along the major drainage paths. An 'average' process rate for the coastal erosion and slope retreat of 0.6 m per 1,000 years, or 0.6 mm per annum has been determined from the age of the continental shelf and the time since its development due to rifting and opening of the Tasman Sea. Whilst this rate will have varied with time, it provides a meaningful regional average. Contemporary Illawarra coastal escarpment retreat rates derived from slopes affected by slope instability all lie within one order of magnitude, from 0.1 to 1 m per 1000 years and most actually fall within half this order of magnitude.

In conclusion, the current rates of retreat suggests the escarpment slopes may have remained in a more or less similar geomorphological form for perhaps the last 50,000 years and possibly even for the last 100,000 – 300,000 years or so.

Areas where landslides are active are likely to have changed significantly within even the last 20,000 – 50,000 years, but other areas where landslides are less active may not have changed significantly for even longer periods. Hence the modern day escarpment can be considered to be of Quaternary age (11,500 years to 5 million years before present) albeit with its precursor slopes extending further back into the Neogene period. Even during the Holocene Period (from the present day extending back to 11,500 years before present) there is likely to have been substantial change within the slopes of the escarpment.

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## 12 REFERENCES

- Campbell, H. J. (2010). New Zealand Geology: A storey of contorted crustal edge effects. In Williams, A.L., Pinches, G.M., Chin, C.Y., McMoran, T.J. and Massey, C.I. (eds). Geologically Active. Proceedings of the 11<sup>th</sup> IAEG Congress, Auckland, New Zealand, 5-10<sup>th</sup> September 2010.
- Cruden, D. M. and Varnes, D. J., (1996). Landslide Types and Processes. In Turner, A. K. and Schuster, R. L., (editors), Landslides, Investigation and Mitigation. Special Report 247. Transportation Research Board, National Research Council. National Academy Press Washington DC
- Davies, P. J., (1975). Shallow seismic structure of the continental shelf, Southeast Australia. Australian Journal of Earth Sciences, 22: 3, 345 – 359.
- Department of Environment, Climate Change and Water, (2009). New South Wales Government Sea Level Rise Policy Statement. ISBN 978-1-74232-464-7, DECCW 2009/708, October.
- Delaney, M.G., (2005). Coastal cliff line stability and regression in the Newcastle Region Australian Geomechanics Society, Vol. 40, No. 1, pp. 31 – 38.
- Gaina, C., Muller, D.R., Royer, J., Stock, J., Hardebeck, J. and Symonds, P., (1998). The tectonic history of the Tasman Sea: A puzzle with 13 pieces. Journal of Geophysical research, Volume 103, Number b6, pages 12,413 – 12,433.
- Flentje, P. and Chowdhury, R. N., (2005). Managing landslide hazards on the Illawarra escarpment. Proceedings of the GeoQuest Symposium on Planning for Natural Hazards – How can we mitigate the impacts? Editor: Associate Professor John Morrison. University of Wollongong, 2-5 February 2005. Published by GeoQuest Research Centre, University of Wollongong 2005, p 65 - 78
- Flentje, P., Stirling, D. and Chowdhury, R.N., (2011). Landslide Inventory, Susceptibility, Frequency and Hazard zoning in the Wollongong and wider Sydney Basin Area. Landslide Risk Management Roadshow 2011 National Seminar Series, Australian Geomechanics Journal, Volume 46, No 2, June, pages 41 – 49.
- Geoscience Australia 2009. Australian Bathymetry and Topography Grid, June (2009).
- Glenn, K. C., Post, A., Keene, J., Boyd, R., Fountain, I., Potter, A., Osuchowski, M., Dando, N. and Shipboard Party, (2008). NSW Continental Slope Survey, Post Cruise Report, RV Southern Surveyor 10/2006. Geoscience Australia Record 2008/14.
- Gordon, R., (2003). Sea level change and palaeochannels in the Perth area. Australian Geomechanics Vol. 38 No. 4, pages 84 – 89.
- Goudie, A. S., (2006). The history and evolution of desert hydrology and landforms: the role of climate change. In, P. D'Odorico and A. Porporato, editors. *Dryland Ecohydrology*, pp. 129-140. Dordrecht: Springer.
- IPCC TAR, (2003). Climate Change 2001, The Scientific Basis. Intergovernmental Panel on Climate Change, Third Assessment Report.
- Korsch, R. J., Totterdell, J. M., Cathro, D. L. and Nicoll, M. G., (2009). Early Permian East Australian Rift System. Australian Journal of Earth Sciences: An International Geoscience Journal of the Geological Society of Australia, 56:3, 381-400.
- Kotze, G., (2007). An assessment of rockfall frequency for the coastal cliff-lines of Pittwater Local Government Area, Sydney. Australian Geomechanics, Vol. 42, No. 1, March 2007. Pages 213 -219.
- Leventhal, A. and Flentje, P., (2012). Illustrative sections depicting landslide susceptibility of the Illawarra escarpment. Australian Geomechanics, Vol. 47, No. 1, March 2012, in press.
- Lyell, C., (1830). *Principles of Geology*.
- Milankovitch, M. (1941). *Canon of Insolation and the Ice-Age Problem*. Israel Program for Scientific Translations. Jerusalem (1969).



- Moon, A.T., Wilson, R.A. and Flentje, P.N., (2005). Developing and using landslide size frequency models. Joint Technical Committee on Landslides and Engineered Slopes, JTC-1, in association with Vancouver Geotechnical Society. Proceedings of the International Conference on Landslide Risk Management/18th Annual Vancouver Geotechnical Society Symposium, Vancouver. May 31 to June 4, pp 681 - 690.
- Muller, R. D., Gaina, C. and Clark, S., (2006). Seafloor spreading around Australia in Veevers, J., (editor) Billion-year earth history of Australia and neighbours in Gondwanaland. School of Geosciences, University of Sydney. [http://www.es.usyd.edu.au/Geophysics/Marine\\_geo-physics/Resprojects/byeh.html](http://www.es.usyd.edu.au/Geophysics/Marine_geo-physics/Resprojects/byeh.html).
- Nanson, G.C., Cohen, T.J., Doyle, J. and Price, D.M., (2003). Alluvial evidence of late-Quaternary climate and flow-regime changes on the coastal rivers of New South Wales, Australia. In: K.J Gregory and G. Benito (Eds), *Palaeohydrology: Understanding Global Change*, Wiley, Chichester (233-258).
- Nott, J., (2003). The Importance of Prehistoric Data and Variability of Hazard Regimes in Natural Hazard Risk Assessment – Examples from Australia. *Natural Hazards*, Vol. 30, pages 43 to 58.
- Quigley, M. C., Sandiford, M. and Clark, D., (2009). Neotectonics and landscape evolution of southeastern Australia: establishing a geologic context for contemporary seismicity. In Clark, D., (Editor), 2009. Potential geologic sources of seismic hazard in the Sydney Basin. Proceedings volume of a one day workshop. *Geoscience Australia Record* 2009/11. 115pp.
- Sdrolas, M., Muller, R. D. and Gaina, C., (2001). Plate Tectonic Evolution of Eastern Australian Marginal Ocean Basins. *Petroleum Exploration Society of Australia, Australasia Basins Symposium*, Melbourne, Victoria 25 – 28 November.
- Shackleton, N. J.; Opdyke, N. D., (1973). Stable oxygen isotope analysis on sediment core V28-238. doi:10.1594/PANGAEA.51710.
- Sloss, C. R., Murray-Wallace, C. V. and Jones, B. G., (2007). Holocene sea-level change on the southeast coast of Australia: a review. *The Holocene* 2007; 17; 999. DOI: 10.1177/095968 3607082415.
- Stone, P. C., (2012). Landslide impacts on the South Coast Railway during the 1988 – 90 El Nino Event, *Australian Geomechanics*, Vol. 47, No. 1, March 2012, in press.
- Thom, B. G., Keene, J. B., Cowell, P. J. and Daley, M., (2010). East Australian marine abrasion surface. *Geological Society special publication* 346(1): 57-69.
- Tobin, P. R., (2012). Managing slope instability hazards affecting local roads within the City of Wollongong. *Australian Geomechanics*, Vol. 47, No. 1, March 2012, in press.
- Tomkins, K. M., Humphreys, G. S., Wilkinson, M. T., Fink, D., Hesse, P. P., Doerr, S. H., et al. (2007). Contemporary versus long-term denudation along a passive plate margin: the role of extreme events. *Earth Surface Processes and Landforms*, 32(7), 1013-1031.
- Vasconcelos, P. M., K. M. Knesel, Cohen, B. E. and Heim, J. A., (2008). Geochronology of the Australian Cenozoic: a history of tectonic and igneous activity, weathering, erosion, and sedimentation. *Australian Journal of Earth Sciences* 55 (6-7): 865-914.
- Young, A. (1972). *Slopes*, Edinburgh: Oliver and Boyd.
- Young and McDougall, (1985). The Age, Extent and Geomorphological Significance of the Sassafrass Basalt, south-eastern New South Wales. *Australian Journal of Earth Sciences*, Volume 32, pp 323 – 331.